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Evaluating the spatio-temporal variation of China's offshore wind resources based on remotely sensed wind field data

Dong Jiang [a,*], Dafang Zhuang [a], Yaohuan Huang [a], Jianhua Wang [b,**], Jingying Fu [a]

[a] State Key Laboratory of Resources and Environmental Information System, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A Datun Road, Chaoyang District, Beijing 100101, China

[b] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Department of Water Resources, China Institute of Hydropower & Water Resources Research, 1A Fuxin Road, Haidian District, Beijing 100038, China

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ABSTRACT

Wind resource assessment in coastal areas is an important concern to develop offshore wind power. The high complexity of coastal environment entails the need for new tools that can describe the spatial variability of wind. In this paper, a distribution study of offshore wind power in China using QuikSCAT Level-2 satellite measurements at a 0.5-degree horizontal resolution was performed. Based on long-term information of daily average wind field, the paper gives an overview of the spatio-temporal distribution of wind resources in China's coastal regions. The results indicate that China has significant offshore wind energy development potential. The total offshore wind energy potential at 10 m in China is approximately 660 GW. The coastal region along Fu Jiang Province has the best wind resource compared with other parts of China's offshore regions. An integrated analysis was made by combining the offshore wind farm plans of coastal provinces with the spatio-temporal characteristics of the wind resource, and suggestions are presented accordingly. We find that the use of wind estimates from satellite data potentially leads to a more refined wind resource analysis.

Contents

* Corresponding author. Tel.: +86 106 488 9433; fax: +86 106 485 5049.
** Corresponding author.
E-mail addresses: jiangd@igsnrr.ac.cn, jiangd@lreis.ac.cn (D. Jiang).
wjh@iwhr.com (J. Wang).

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1. Introduction

1.1. Offshore wind resources in China

With its rapid development in the past 30 years, China is now facing an increasing demand for energy. Alternative sources of energy, especially clean and renewable energy are of great interest. Wind power is the fastest growing renewable energy source. During the last decade, wind energy growth rates worldwide averaged approximately 30 percent annually [1]. In China, the total installed wind power capacity rose from 2.60 GW in 2006 to 44.73 GW in 2010. The newly installed wind capacity of China in 2010 was 18.93 GW, comprising 43 percent of the world's total [1,2]. According to the plan set forth by the Chinese government, the total installed capacity will reach 100 GW by the end of 2015, which means approximately 3 percent of China's power consumption will be supplied by wind [3].

China has abundant wind resources, which are mainly concentrated in the northeast, northwest and north of mainland China and along the coast [2]. In the 18,000-km-long coastline along the southeastern coast, there are more than 5000 islands in the near shore area. These regions, with a wind power density greater than 200 W/m^2, have the richest wind resources [4]. The estimates of China's offshore wind resource potential vary from 600 GW (UNEP, 2004) [5] to 750 GW (China Meteorological Administration—CMA, 2003) [6]. At the end of 2009, the Wind Energy and Solar Energy Resources Evaluation Centre of CMA estimated China's offshore wind potential at 550 GW, and 200 GW of class 3 wind power was distributed at water depths of 5–25 m [7]. Considering technical constraints, such as the efficiency of a turbine rotor, wind turbine downtime for schedule maintenance, electrical conversion loss, layout efficiency of a wind farm, etc., the estimated exploitable potential is approximately 2405 TW h within the exclusive economic zone (EEZ) of China by the year 2020 according to Hong and Möller [8]. According to the energy plan of the Chinese government, interest in offshore wind resources has increased in recent years. The first 1.5 MW offshore wind farm, located at a water depth of 30 m and 70 km from the coast in Bohai Bay, was established in November 2007. Soon after, the 102 MW Shanghai Donghai Bridge wind farm was established off Shanghai's coast [9]. Currently, several offshore wind farms are under construction and more projects are being planned by coastal provinces. According to the *General Requirements and Tasks for Energy Work in 2010* by the National Energy Administration of China (NEA), the total installed capacity of offshore wind power will reach 5 GW by 2015 and 30 GW by 2020. To accomplish this goal, the Chinese government has recently formulated several policies. In early 2010, *Interim Measures for the Administration of Offshore Wind Power Development* was published by the National Energy Bureau and the State Oceanic Administration, to standardize offshore wind farm site selection and wind farm construction. Soon after that, *Access Standards for Wind Power Equipment Manufacturing Industry* was issued by the Ministry of Industry and Information Technology of China, which gave priority to the industrialization of offshore wind turbines.

China has witnessed rapid development of offshore wind energy in recent years. However, compared with land wind power, wind energy faces complex conditions in offshore areas. The unavailability of accurate and detailed wind information is one of the main obstacles for wind energy planning. In situ observations, such as buoys and masts, are much sparser than that on land, and year-long time series of meteorological data are generally unavailable. In addition to the total offshore wind potential given by the above mentioned assessments, details about the spatial and temporal variations of wind fields are also important. Therefore, an operational method for deriving long-term wind field data in offshore regions is urgently needed for the accurate assessment of offshore wind resource in China.

1.2. Evaluation of offshore wind resource with remote sensing data

Due to the development of remote sensing techniques, recent studies have indicated that offshore wind fields can be retrieved from backscattering coefficients according to the relationship between the measured roughness of the sea and the wind speed. Satellite-derived sea surface winds can be used to supplement in situ measurements and model simulations. With the successful launch of the sea satellite SEASAT by the US since 1980s, the microwave scatterometer has became an operational tool for the sea surface wind field monitoring at global scale [10,11]. Scatterometer instruments on board satellites can routinely provide estimations of surface wind vectors with high spatial and temporal resolution over all ocean basins. These types of sensors include SEASAT-SASS, QuikSCAT-SeaWinds, ADEOS-NSCAT, and XERS-AMI-Wind of the European Space Agency (ESA). Since July 1999, NASA's SeaWinds scatterometer on board QuikSCAT has provided surface wind estimates. The accuracy of the wind speed derived from the scatterometer is approximately ± 2 m/s, the spatial resolution is 25–50 km, and the temporal resolution is 1 day [12]. Another widely used satellite data source for wind mapping is Synthetic Aperture Radar data, which has a 100–400 m spatial resolution [13,14]. However, the temporal resolution is relatively coarser (2 to several weeks), and the scene width is small compared with that of the QuikSCAT scatterometer. Therefore, we prefer using scatterometer data for large-scale wind resource analysis.

Global and regional studies of offshore surface wind power distributions with QuikSCAT wind products have been performed. Felipe et al. used both on-site marine meteorological data and QuikSCAT data to evaluate the location, seasonal timing, and availability of the wind power resource for the southern coast of Brazil. Maps of wind speed, wind power density were presented [15]. Ali evaluated feasibility study of offshore wind turbine installation in Persian Gulf and Gulf of Oman in southern parts of Iran using QuikSCAT data and meteorological data [16].

Ioanna et al. compared mean winds from QuikSCAT with reanalysis data from the Weather Research and Forecasting (WRF) model and in situ data from the FINO-1 offshore research mast in the Northern European Seas. The result demonstrated the applicability of satellite observations as the means to provide information useful for selecting areas to perform higher resolution model runs or for mast installations [17]. Oh et al. provided a summary of the offshore wind resources of the Korean Peninsula, by analyzing marine buoy datasets and the QuikSCAT satellite data measured over 9 years [18]. Karamanis et al. evaluated wind energy resources in the Ionian Sea in the Ionian Sea of Western Greece. A good agreement of the QuikSCAT data to buoy data in all the range of wind speeds, although wind speed retrievals from QuikSCAT at nearshore stations are not as accurate as compared to offshore stations due to land contamination [19]. Long term QuikSCAT wind data also have been used in small regions (for example, gulf region). Philippe et al. used the QuikSCAT wind data from 1999 to 2006 as the reliable wind distribution reference in St. Lawrence River and Gulf region, Canada [20]. In China, Liu and He analyzed the statistical character of offshore wind in the South Sea, China. Wind fields from QuikSCAT data were compared with meteorological stations data of 7 little islands. The result indicated that a close relationship existed between QuikSCAT data and in situ observations [21]. In 2009, supported by the project 'Off-Shore Wind Energy Resource Assessment and Feasibility Study of Off-Shore Wind Farm Development in China, off-shore wind energy resources in typical regions of China were assessed by China Meteorological Administration (CMA). QuikSCAT data and

satellite SAR data were adopted as supplement to convenient ground observations [22].

1.3. The main objective of this study

The main objective of this study was to provide a comprehensive assessment of China's offshore wind potential based on nine years (2000–2008) of wind field data derived from satellite imagery. An overview is presented for the first time that cover not only the total wind resource potential but also the spatio-temporal characteristics of wind fields in the coastal regions of China. An integrated analysis was performed combing offshore wind farm plans of coastal provinces with the spatio-temporal characteristics of the wind resources. We conclude this paper with relevant suggestions. Possible constraints on offshore wind exploration, including technical and economical factors, are beyond the scope of this study and need further verification.

2. Data acquisition

In compliance with the requirements of wind resource assessment, remotely sensed wind field data, in situ measured wind data, and some auxiliary data were used in this study.

(1) Remote sensing measurement of wind field data. QuikSCAT wind field data, retrieved from NASA's QuikSCAT-SeaWinds database, were used for offshore wind resource assessment. The data cover China's entire coastal area with a spatial resolution of 50 km. Daily QuikSCAT wind field products from 2000 to 2008 were provided by the Center for Satellite Exploitation and Research of France (CERSAT). The data were originally in ASCII format and contained information about locations (i.e. longitude, latitude), and wind vectors (i.e. wind speed, zonal and meridional wind speed; wind stress, zonal and meridional wind stress). We wrote a program to convert the data into real wind field information (wind speed and wind direction) in the ArcGIS GRID format allowing further spatial statistics and wind data analysis to be performed with convenience.
(2) In situ mast measurements. In situ wind data measured at four wind masts (serial number: 0841, 0842, 0871, 0872) in four high-wind regions on Putian Island of Fujian Province in southeast China were provided by Institute of Energy Research of the National Reform and Development Committee. The four points were located within a pixel of the QuikSCAT wind field product. Wind velocities were measured for every 2 s at each mast. The 10-min averages were automatically calculated from the 2-s samples. The data were then accumulated to daily values for comparison with remotely sensed wind data.

Other auxiliary data, such as bathymetry and coastline data, were provide by the Data Center for Resources and Environmental Sciences (RESDC) of the Chinese Academy of Sciences.

3. Methodology

To estimate the offshore wind resource with remote sensing techniques, the following basic steps were as followed (Fig. 1).

(1) Derive wind field feature information (wind vector and direction) from the QuikSCAT wind field product, and convert the data into ArcGIS raster file format.
(2) Validate the satellite-derived wind field data with in situ observed wind data.
(3) Analyze the spatio-temporal characteristics of the wind field and assess wind resource.

3.1. Retrieval of wind filed data

The scatterometer transmits microwave pulses and receives backscattering power from the ocean surface. The backscattering power was measured to estimate the normalized cross section (σ_0) of the sea surface [23]. The backscattering cross section is strongly influenced by waves created by local wind. Hence, wind vectors can be indirectly retrieved from this relationship [24,25]. A relationship between the wind vector at a 10 m height above sea level and σ_0 has been empirically estimated for open seas[25]:

$$\sigma_0 = F(U, \theta, \lambda, P) \quad (1)$$

where σ_0 is the backscatter cross section; U is the wind vector (including wind speed and direction); θ is the angle of incidence of microwaves from the scatterometer; λ is the wave-legth of the radar wave; and P is the polar mode used.

To date, the most widely used algorithms include the CMOD-4 and the CMOD–IFR2 model. These algorithms were established by combining scatterometer data with in situ measurements, including buoy data. Further details about wind vectors retrieval can be found in previous studies [20,26].

3.2. Assessment of offshore wind resource

The criteria for determining wind energy potential is based on a set of parameters that includes the average annual wind power density (W/m^2), the mean annual wind speed (m/s), the annual hours of wind speed above 6 m/s, and the annual hours of wind speed above 3 m/s [27]. The wind power density that characterizes the wind power available at a particular place is given by the average power per unit area exposed to wind, due to temporal variations of wind [28]. The average wind power density can be calculated from wind speed information.

$$\omega = \frac{1}{2n} \Sigma_{i=1}^{n} (\rho_i V_i^3) \quad (2)$$

where ω stands for the average wind power density (in w/m^2); n is the number of wind speed observations; ρ_i is the ith air density (in kg/m^3); and V_i is the ith wind speed (in m/s). Further details about

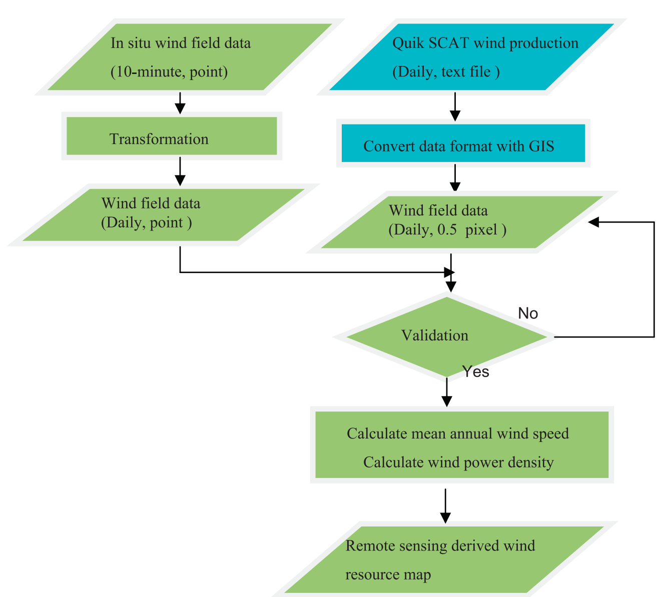


Fig. 1. Flowchart of remote sensing based offshore wind resource assessment.

wind power density estimation can be found in previous studies [29].

Based on the QuikSCAT wind field product and formula (2), the wind power density data at a 0.5-degree spatial resolution for China's offshore areas in the past 9 years were obtained. The datasets were in raster format (Arcgis GRID format). Further spatial, statistical and time series analyses were conducted with these datasets.

4. Results and analysis

4.1. Results of wind field retrieval

Daily and annual average wind speed and wind direction data were derived from the daily QuikSCAT wind field product from 2000 to 2008 using the method mentioned in Section 3.1. Fig. 2 shows the wind speed averaged over 9 years for China's offshore areas. The highest wind speed was mainly found in the South Sea, especially for the coastline along Fujian Province and the Taiwan Strait (Fig. 2). This result is consistent with those of existing studies, but this dataset presented greater spatial and temporal detail, which enhanced further analysis and assessment.

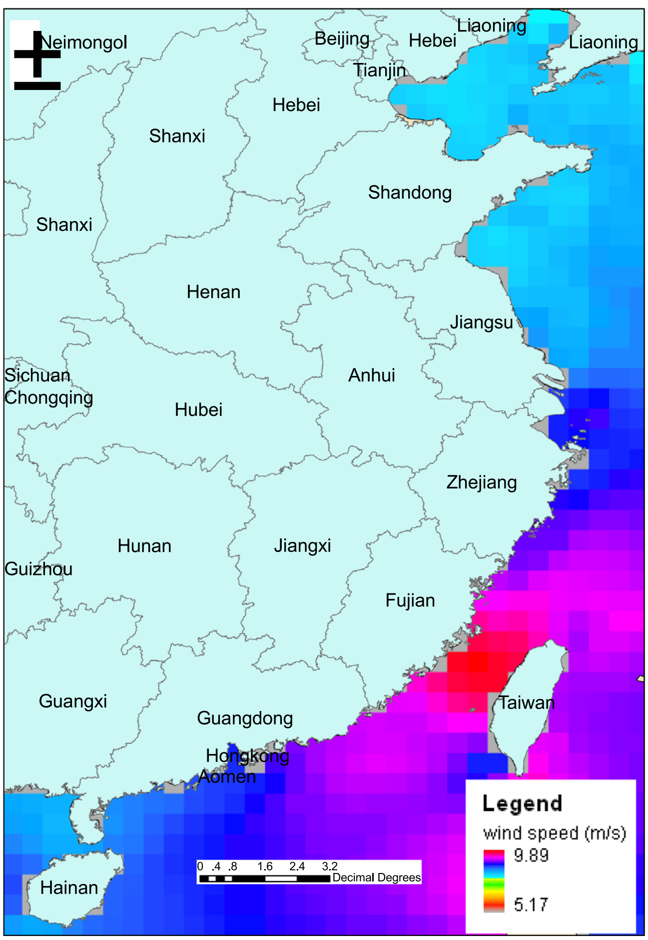


Fig. 2. Offshore Wind speed and spatial distribution (m/s): 9 years average.

The wind velocity data averaged at the four sites in Putian Island of Fujian Province were used for correlation analysis with remotely sensed wind data. Fig. 3 shows the comparison of in-situ measured mast data and satellite-derived wind speed (daily average, taking 2004 as a case).

The results indicate that the wind speed profile derived from remote sensing agreed well with the in situ mast-measured wind profile. A standard deviation of 1.3 m/s with an R^2 of 0.71 was found for the two types of wind data by correlation analysis. The comparison indicates that the remotely sensed wind data were closely related to the in situ wind measurements. In fact, the accuracy of the QuikSCAT wind field product has been evaluated by comparison with buoy wind data globally. A wind speed of 2–24 m/s can be retrieved with a normal accuracy of ± 2 m/s [24]. A detailed validation can be found in previous studies [24,26]. The daily QuikSCAT wind field product allows a continuous spatio-temporal observation of offshore wind vectors. Therefore, a reasonable assessment of wind resource in offshore areas can be achieved based on these data.

4.2. Wind resource assessment

A nine-year average monthly wind power density map (Fig. 4a–f) and the annual map (Fig. 5) were obtained according to the methods introduced in Section 3.2.

Fig. 5 presents the spatial variability of the wind resource in the coastal area. Based on the long-term average wind mean power density data, the total wind resource within 100 km off the coast was calculated to be approximately 668 GW. The offshore areas in the East Sea and the South Sea have high wind power potential. The 9-year average wind speed and wind power density of the offshore areas in the East Sea are 7.4–9.6 m/s and 450–650 W/m^2, respectively, and those of the offshore areas in the South Sea are 6.3–9.5 m/s and 350–600 W/m^2, respectively. The Taiwan Strait region seems to have the highest potential in these areas compared with the Bo Hai Sea Gulf and the Yellow Sea. The wind power densities of the offshore areas in the Bo Hai Sea Gulf and the Yellow Sea are approximately 250–350 W/m^2 and 250–400 W/m^2, respectively. The seasonal variabilities of the wind power densities are obvious: the wind power density in the East and the South Seas are larger from August to December, reaching their peak in October. For some places near the coastline of Jiangsu Province in Yellow Sea, the maximum wind power density occurs in August.

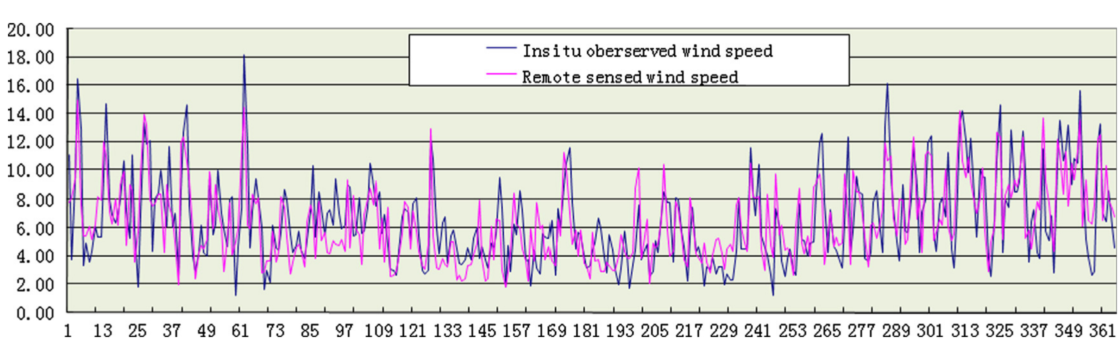


Fig. 3. Comparison of in situ mast measured and satellite-derived wind speed (daily average, 10 m height). Putian County, Fujian Province, Southeast China.

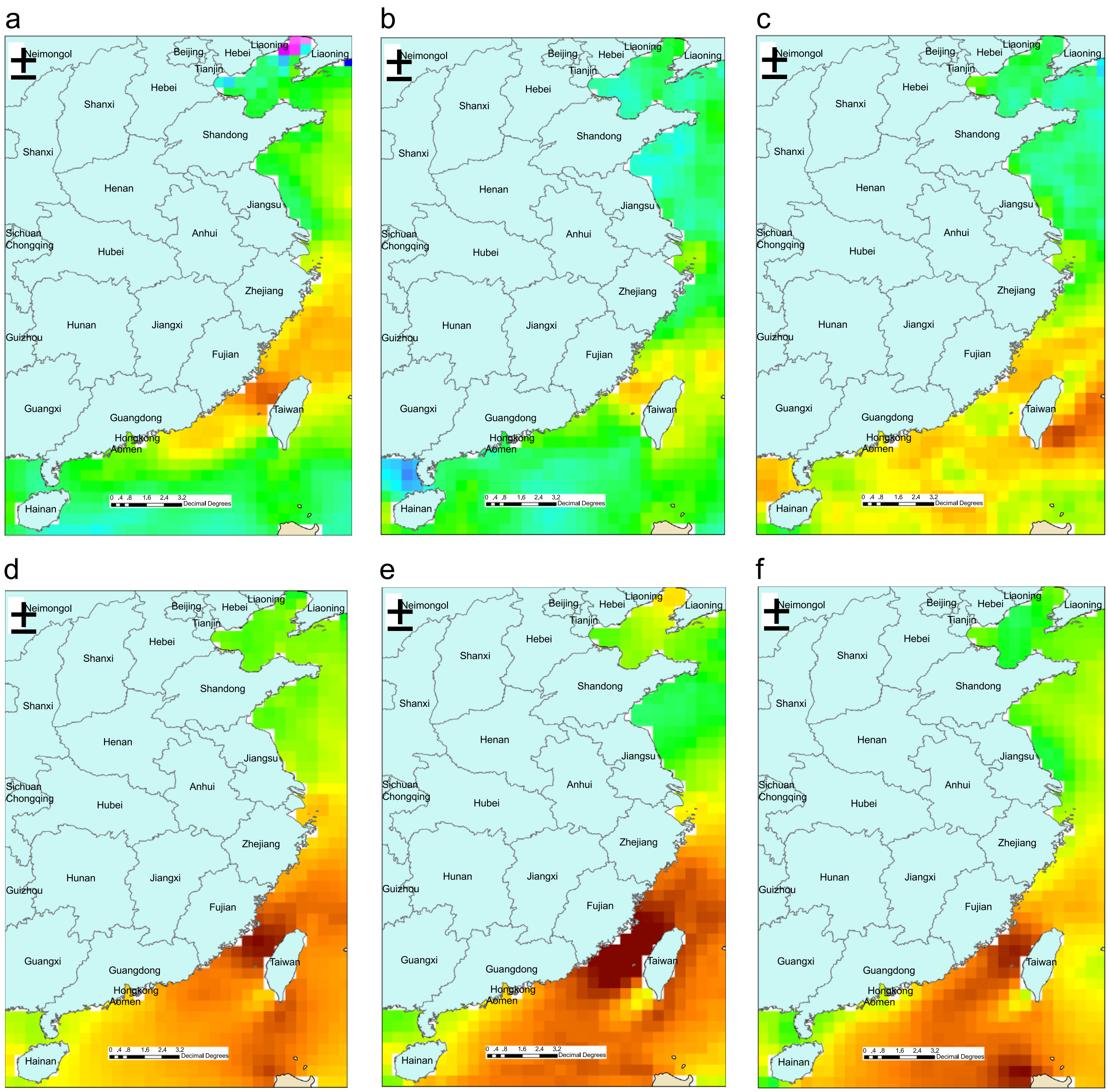


Fig. 4. Nine-year average monthly wind power density map of coastal regions of China (W/m^2). (a) Feb. (b) April. (c) June. (d) Aug. (e) Oct. (f) Dec.

In China, national wide assessment of wind resources have been done twice in 2001–2003(CMA-2003) and 2008–2009 (CMA-2009), and were mainly based on in situ observed data. Both buoys and meteorological stations are very sparse in the large offshore regions of China, so that the accuracy varied dramatically, especially in large ocean regions without any site data nearby. The overall trends of wind resources in offshore regions of China of CMA-2003/CMA-2009 and our result are similar. In recent years, many masts have been established in these regions, but the historical data are not available. The accuracy of the site-based results varied dramatically, especially in large ocean regions without any site data nearby. In addition, the QuikSCAT wind field product presented systematic estimates from space and has been evaluated globally. Based on these data, we presented a spatial continuous assessment of offshore wind resource with 0.5 degree spatial resolution. In addition, the update of offshore wind resources based on in situ data were time consuming. Supported by remote sensing techniques, the assessment could become very convenient. The daily source data is available since 1999. The temporal continuous offshore wind resources of China could be estimated operationally within 30 min with method presented.

4.3. Offshore wind planning vs. wind resource potential

Stimulated by energy demands and government policy, China's offshore wind energy has been developing rapidly in recent years. In September 2010, four pilot offshore wind projects were launched in Jiangsu Province as the first round of concession projects by the National Energy Administration [7]. The total wind turbine capacity is 1 GW, which is provided by two inter-tidal wind farms, each with 200 MW capacity, and two offshore wind farms, each with 300 MW capacity [9]. All four projects will be completed within 3 years. Apart from the existing projects, 5 costal provinces have proposed ambitious plans for offshore wind farm development for 2015–2020. The total wind power capacity planned by the 5 provinces will exceed 10 GW by 2015, which is twice the goal of the NEA. The offshore wind farm plans of another two coastal provinces, Guangdong and Hainan are underway [30–33]. China's offshore wind power will make significant progress in the near future, and the demand for a refined assessment of spatial and temporal variation of wind power will increase accordingly.

Based on a comparison of wind farms under planning with the mean wind power density map (Table 1, Fig. 4), we find that the

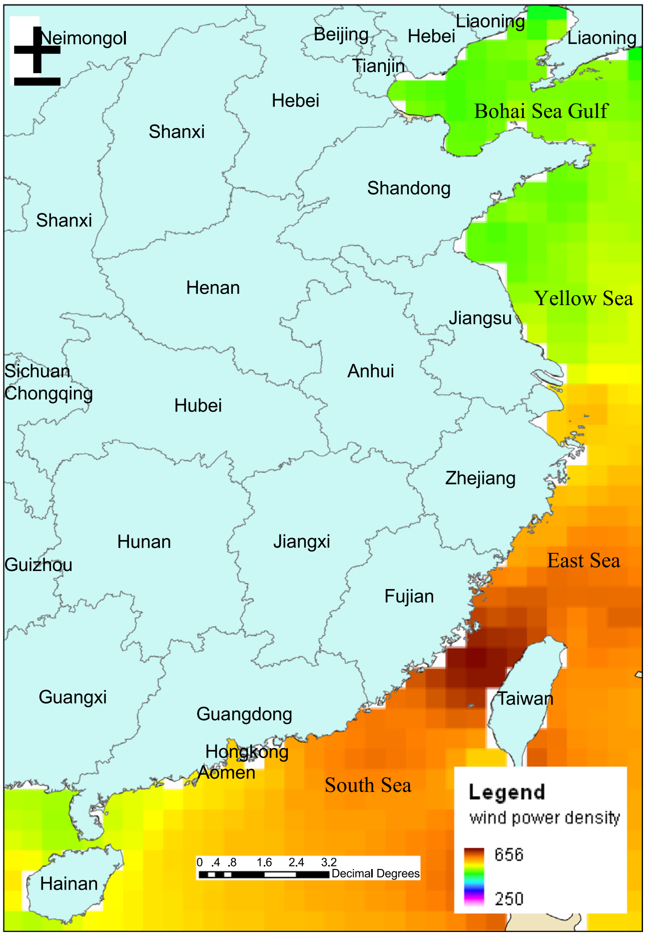


Fig. 5. Nine-year average annual wind power density map of coastal regions of China (W/m^2).

Table 1
Offshore wind farm planning of coastal regions of China.

Province	Planning capacity (GW), by 2015			Planning capacity (GW), by 2020		
	Inter-tidal	Offshore*	Total	Inter-tidal	Offshore	Total
Shang Hai	0.10	0.60	0.70	0.20	1.35	1.55
Shan Dong	1.20	1.80	3.00	1.20	5.80	7.00
Jiang Su	2.60	2.00	4.60	2.90	6.55	9.45
Zhe Jiang	0.20	1.30	1.50	0.50	3.20	3.70
Fu Jian	0.10	0.30	0.40	0.30	0.80	1.10
Total	4.20	6.00	10.20	5.10	17.70	22.80

* *Note*: Offshore region with 5–50 m water depth.

most ambitious plans have been proposed by Jiangsu Province near the Yellow Sea and Shandong Province near the Bo Hai Bay, where the mean wind power densities are relatively low. The offshore areas near the coastline of the Fujian and Zhejiang provinces are more suitable for the development of offshore wind farms (Fig. 4). However, their goals of offshore wind farm development are much less ambitious than those of other provinces.

5. Conclusion

Wind resource assessment in coastal areas is important for offshore wind power development. The environmental complexity of the coastal areas implies the need for new tools to describe spatial wind variability. This paper investigated the available offshore wind energy resource in China using remote sensing techniques. Based on the long-term daily average wind field derived from QuikSCAT data, we gave an overview of the spatio-temporal distribution of the wind resource in China's coastal regions. The results indicate that China has significant development potential for offshore wind energy. The total offshore wind energy potential is 660 GW. We found that the coastal region in the South Sea had the best wind resource potential compared with other parts of the offshore regions of China.

We also found that the use of wind estimates from satellite data may lead to more refined wind resource analysis. Both buoys and meteorological stations are very rare in the large offshore regions of China, so that the accuracy of results based on in situ observations varied dramatically, especially in large ocean regions without any site data nearby. The QuikSCAT wind field product presents systematic estimates from space and has been evaluated globally. Based on these data, we presented a spatial continuous assessment of offshore wind resource with a 0.5-degree spatial resolution. Moreover, the update of offshore wind resources based on in situ data were time consuming. Supported by remote sensing techniques, the assessment could become very convenient. The daily source data is available since 1999. The temporal continuous offshore wind resource of China could be estimated operationally within 30 min with method presented.

Further studies may be focused on the combination use of scatterometer data, satellite SAR mages from RADARSAT, ENVISAT and in situ observations (if available) to improve offshore wind resource assessment and site selection for wind turbines.

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